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ON THE RHYTHM OF THE MAMMALIAN HEART.

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THE following investigation was conducted on the hearts of various mammals—cats, dogs, rabbits, hedgehogs, guinea-pigs, and rats. The cat was the animal usually employed, and the statements contained in this paper are all to be regarded as applicable to the heart of that animal, unless where otherwise specified.

The experiments were performed (1) partly on the excised heart—sometimes with an artificial circulation kept up, and sometimes not—and (2) partly on the heart in situ. In the latter case, the animal was anæsthetized (usually with chloroform) and secured on a Czermak's holder, means being taken to maintain the temperature as far as possible. Artificial respiration was employed and the chest was laid open; in some cases the pericardial sac was left intact, but in most of my experiments it was opened and the heart fully exposed.

In some cases direct observation of the organ was kept up during the entire experiment; in many instances the action was graphically recorded in addition to frequent direct observation of the heart.

Various arrangements were employed for registering the contractions of the auricles and ventricles. The auricular action was usually recorded by connecting one of the appendices by means of a thread with (1) a horizontal lever suspended by an elastic band and writing directly on a revolving cylinder or (2) with a receiving tambour which again communicated with a recording tambour.

The ventricular beats were recorded in a variety of ways, most commonly by one or other of the following—

(1) A light lever resting on the ventral surface of the ventricles and marking upon a smoked drum.

The ventricles rested on a boat-shaped plate of vulcanite, which was slipped underneath them and rigidly held in position.

(2) A float resting upon the ventricular surface and communi-

cating with a receiving tambour, a recording tambour being attached in the usual fashion.

The ventricles rested on a support similar to that just mentioned.

(3) An instrument on the principle of Marey's *pince cardiographique.* The movements were transmitted from the *pince* by a system of tambours.

I. SOME FEATURES IN THE BEHAVIOUR OF THE MAMMALIAN CARDIAC MUSCLE UNDER THE INFLUENCE OF DIRECT EXCITATION.

On the effects of direct stimulations of different strengths.

A conspicuous feature in the behaviour of the cardiac muscle of cold-blooded animals under the influence of single stimuli is the fact that minimal stimulation is at the same time maximal. The contraction excited by a strong induction shock is no larger than one excited by a weak induction shock of strength just sufficient to act as a stimulus; whatever be the strength of the excitation applied, provided it is strong enough to cause contraction at all, the response is always maximal (Bowditch, Von Basch, Kronecker and Stirling). This law seems also to hold in the case of single stimuli, other than electrical (e.g. mechanical or thermal stimuli); it constitutes a fundamental point of difference between the behaviour of the cardiac muscle and that of voluntary muscle.

As the result of a large number of experiments on the mammalian heart I find that the same law holds good.

My experiments bearing on this point were conducted—

(1) On the excised heart which had just become quiescent. A regular series of induction shocks (every half second, second, or two seconds) was applied. The contractions were recorded by a light lever resting on the ventricles.

(2) On intact hearts in situ, brought to a standstill by vagus stimulation.

(3) On slowly beating intact hearts in situ; the slow action resulting from cooling of the animal &c.

In the first series of experiments—on excised hearts the ventricles of which had ceased to beat spontaneously but were still quite excitable to direct stimulation, I registered the ventricular contraction by means of a light recording lever resting on the anterior surface of the ventricles. Single induction shocks were sent in at regular intervals so as to excite the quiescent muscle; weak and strong shocks were alternately used. The strong shocks were obtained with the secondary coil of a Du Bois induction machine at 0, a Daniell's cell being employed in the primary circuit. The weak shocks were usually of such a strength as was just sufficient to excite contraction; the secondary coil often standing at 10—14 cm.

The tracings obtained show that the strength of the beats occurring in response to a series of alternately weak and strong shocks is entirely independent of the strength of stimulus applied. The contractions excited by the weak shocks are quite as strong as those following the application of the strong shocks; any variations in strength seem to depend on other causes.

Minimal stimulation is evidently at the same time maximal. (See Pl. III. Fig. 1.)

In the second series of experiments, the heart was examined in situ with the normal circulation going on.

A pair of small electrodes were fixed in contact with the ventricle apex, and through these a regular automatic series of induction shocks at the rate of two per second could be sent. By means of a reverser it was easy to use minimal or maximal shocks as desired.

The right vagus nerve was then stimulated in the neck. When the heart had been inhibited and reduced to a state of quiescence, a couple of minimal shocks were applied to the ventricles, then a couple of maximal shocks, then minimal ones again and so on, weak and strong shocks in alternating pairs.

The results obtained are quite decisive of the point in question; the tracings show plainly that the strength of contraction does not depend on the strength of the exciting shock; the beats occurring in response to the weak shocks are as strong as those caused by the strong shocks. (Pl. III. Figs. 2, 3, and 4.)

As regards the absolute strength of beat occurring in response to direct stimuli there is a wide range of variation when the heart is examined in inhibited conditions, but when the organ is not markedly under inhibitory influence, as in the third series of experiments, some definite and constant results can be obtained.

The absolute strength of contraction occurring in response to a stimulation is largely influenced by the length of time that has elapsed since the preceding contraction—by the degree in which the tissue has recovered from the effects of the preceding beat. Each beat has an exhausting effect and if another beat is forced prematurely, i.e. artificially excited before the cardiac tissue has fully recovered, the beat so forced is a weak one; its precise strength varies (in the absence of disturbing causes) according to the stage at which the process of reparation has arrived (Pl. III. Fig. 5). Caeteris paribus, the strength of contraction manifestly depends up to a certain point on the time that elapses between the forced beat and the preceding one; of course when a length of time sufficient to allow of complete recovery has intervened, the beat will be a maximal one; no further increase in force will result from a further prolongation. The exact period required for complete reparation between the contractions and consequently for the exhibition of maximal beats naturally varies in different conditions of the cardiac tissue.

The great difference between minimal and maximal excitation is that maximal stimuli can "force" a beat when minimal stimuli are quite unable to do so. The tendency of the cardiac muscle to contract in response to artificial excitation undergoes a regular and periodic variation with each cardiac cycle. Immediately after an effective stimulation, there occurs the "refractory period." When a systole has occurred, when the cardiac muscle having contracted to its full extent has begun to relax visibly, it is usually capable of discharging a second beat, but only in response to strong excitation; minimal stimuli are quite ineffective. The later the stimulation comes after the summit of the contraction, i.e. the more the muscle is allowed to relax, the more responsive does the tissue show itself to direct excitation; the less is the strength of stimulus necessary to "force" a beat. The energy of the contraction rises at the same time. Moreover, for a certain time after the process of relaxation is completed and the pause has begun there can often be seen to be a continued rise in the cardiac excitability; the result of stimulation varies in some measure according to the precise time at which it is applied.

Hence it is obvious that there occurs a rhythmic rise and fall in the excitability of the heart; a fall immediately succeeding the occurrence of an effective stimulation, followed by a gradual rise extending through the phase of active relaxation and to a variable extent into the phase of quiescence. This rhythmic rise and fall affects the cardiac excitability both as regards—

(*a*) the force of contraction, and

(*b*) the facility with which a contraction may be elicited, as measured by the strength of stimulus required to induce a beat.

The behaviour of the mammalian heart in these respects is very similar to what has been described by Marey and others in the case of the frog's heart.

Relation of rate of spontaneous rhythm to force of individual ventricular beats.

My observations on the action of the mammalian heart as seen after the thorax has been opened lead me to conclude, that, in such circumstances at least, the rate of beat is usually too quick to allow of the exhibition of systoles of the highest possible strength. The intervals between the beats are so short that one contraction occurs before complete reparation from the effects of the preceding beat has had time to occur; the interval is not long enough to permit of a full accumulation of energy in the contractile mechanism. Hence a simple slowing of the rate (unaccompanied by any force-depressing influence) causes an increase in the strength of the individual beats. Such an augmentation of force may be seen when a "compensatory pause" occurs in sequence to a phase of artificially excited acceleration of the cardiac rhythm. The beat coming immediately after the elongated interval called the "compensatory pause" is usually much enlarged. (Pl. III. Fig. 6.)

Certain forms of vagus influence also can induce a slowing of the cardiac rhythm without exerting any perceptible influence of a direct character upon the ventricles. Such a slowing of the heart's rate is accompanied by a marked increase in the size of the individual ventricular beats.

Of course it may be suggested that the increased distension of the cavities of the heart at the beginning of each beat during a period of slowed rhythm might directly determine an increase in the strength of the ventricular beats. But such a hypothesis would not fully meet the case, as the increase in contraction force during simple slowing occurs even when the superior and inferior venæ cavæ have been clamped, and the cavities of the heart have ceased to be distended with blood.

On the other hand a simple increase in the cardiac rhythm usually causes a marked diminution in the size of the individual beats. (See Fig 5, Pl. III.) The time available for reparation between the contractions is curtailed; there is less energy available for each individual discharge. In this way an extreme reduction in the beats of both auricles and ventricles may be readily brought about. The acceleration necessary to lead to this result is easily caused by the application of any stimulating influence to the pulsating terminations of the great veins, e.g. heat, faradic or galvanic currents (Fig. 6, Pl. III. and Fig. 9, Pl. IV.). Atropin may be administered to eliminate inhibitory influences.

The great weakening of the individual beats that accompanies a simple acceleration of rhythm is not due to the fact that less time is available for the filling and distension of the cardiac chambers between the systoles; a great depression force still presents itself as an immediate accompaniment of acceleration when the great veins opening into the right auricle have been clamped.

Influence of galvanic current.

The passage of a galvanic current of suitable strength through any rhythmically contracting portion of the cardiac tissue usually causes an acceleration in the rate of beat; the degree of acceleration varies according to the excitability of the tissue and the strength of current employed. (A current of too great intensity leads to the occurrence of fibrillar contraction when applied to excitable ventricles.) This influence of galvanic currents may be readily observed either in the intact heart, in the excised organ, or in the isolated apical portion of the ventricles.

Upon quiescent cardiac tissue galvanic currents also act with considerable effect; they can excite a rhythmic series of beats. This influence may be conveniently studied on the ventricles of a heart which has been inhibited by vagus stimulation, or on the ventricles of an excised heart, or on the amputated ventricle apex. In all cases a periodic series of contractions at a greater or less rapidity can be observed; a result that recalls the similar influence of galvanic currents upon the isolated apex of the frog's heart.

Influence of weak faradic current.

Weak faradic currents induce effects similar to those of galvanic currents in (1) causing an acceleration of the rate of beat in a heart already contracting rhythmically, and in (2) leading to the appearance of a periodic series of beats in quiescent but excitable tissues.

Comparative effects of slowly-interrupted and rapidly-interrupted currents.

Some years ago I found that in the hearts of the eel, tortoise, and other cold-blooded animals, especially when the heart had been experimented on for some time, a very marked peculiarity was manifested in regard to the influence of interrupted currents[1]. The contractions of the ventricular muscle in response to slowly interrupted currents are much more rapid than in response to rapidly interrupted currents. A series of induction shocks at 5 per second applied to a quiescent ventricle is much more effective than a series of precisely the same strength at 50 or 100 per second.

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[1] This *Journal*, Vol. vi.

Moreover the rate of rhythm excited by the alternately shutting off and on a rapidly interrupted current is much more rapid than that resulting from the steady continuance of the same current.

This peculiarity observed in the behaviour of the cardiac tissue of cold-blooded animals can be shown to be repeated in the mammalian ventricles, when the latter are tested in a state of markedly depressed excitability—from want of blood-supply, cooling etc. In an excitable heart, fibrillar contraction (heart-delirium) would of course be at once induced by applying interrupted currents to the ventricles, but in depressed conditions, in the cat, rabbit, rat, guineapig, and hedgehog, this difficulty is obviated, and the influence of slowly interrupted currents may easily be compared with that of rapidly interrupted currents &c.

In the dog's heart it is more difficult to avoid the occurrence of fibrillar contraction, and it is only in advanced conditions of depression (e.g. in the amputated apical portion of the ventricles) that the point in question can be readily tested.

II. ON THE ORIGIN OF THE SPONTANEOUS RHYTHM OF THE HEART.

As in all vertebrate animals the mammalian heart-beat partakes of the nature of a progressive contraction beginning at the base or venous end of the organ. The orderly series of events constituting a cardiac contraction is initiated near the termination of the great veins in the right and left auricles. It is very difficult however to make certain in what precise locality the movement begins in the mammalian heart, whether exactly at the junction of the great veins with the auricular tissue or in the terminal portions of the great veins at some little distance from the veno-auricular junction. In a slowly-contracting dying heart the contraction can sometimes be very distinctly seen to begin at the veno-auricular junction; thence it spreads backwards over the great veins for some distance, and onwards over the auricles; subsequently over the ventricles.

But such an origin and sequence of the contraction in the dying organ does not make it at all certain that a similar mode of action holds good in the normal heart. In the dying heart the contraction sometimes shows a tendency of contraction to originate at the junctional parts of the organ—in the auricles at the auriculo-ventricular groove, as well as at the veno-auricular junction. Moreover contraction sometimes seems to begin in the ventricular substance. Indeed the action of the dying organ appears to be modified not only in regard to the slowness and feebleness of its contraction, but in other essential characters, and its features are not to be relied upon as giving an accurate result in regard to the origin and course of the normal spontaneous rhythm.

In the rabbit, rat, hedgehog and some other animals the contraction of the great veins can be studied more easily than in the cat and dog, on account of the presence in the former of a left vena cava superior possessing as it does a pulsatile terminal portion of considerable length. In these animals the venous contraction distinctly appears to occur first, initiating the cardiac beat. And when possible inhibitory influences have been set aside by the administration of atropin, I find that the forcible application of a clamp at the veno-auricular junction—so as to crush the tissue and destroy all vital connection between the vein and the auricle—does not cause an arrest of the rhythmic pulsation of the vein; nor as far as I have seen does it even cause any diminution in the rate of the venous rhythm. The beat in the left vena cava superior goes on as before when its nervous and muscular connections with the auricle have been destroyed; it seems to possess within itself the essential conditions for spontaneous rhythmic action and that action at such a rate as to correspond with the rate of beat in the uninjured heart as a whole.

These facts favour the view that in the cat and dog as well as the normal origin of the contraction is in the venous wall. It may, in any case, be safely affirmed that the spontaneous contraction in the mammalian heart arises in the terminal (or ostial) portions of the great veins either exactly at their junction with the auricles, or in the walls of the veins at some little distance from the actual junction.

The occurrence of the contraction appears to be simultaneous on the right and left sides; at the ending of the venae cavae (chiefly the superior) in the right auricle and the pulmonary veins in the left auricle. The processes that underlie the rhythmic contraction appear to be accurately timed so as to coincide on the two sides, just as in many cold-blooded animals e.g. in the eel[1], where the dominant portions of the heart, the right and left ostial parts of the sinus, beat simultaneously.

As regards the precise tissue in which the rhythmic discharge is generated there is no sufficient evidence available to prove clearly whether the rhythm is dependent on the functioning of nerve cells or of muscular fibres, whether it is a nervous or a myogonic rhythm. Much has of late been said in support of the independent rhythmic power of muscle in various situations, both in the case of non-striated muscle—as in the ureter[1], &c. and in the case of cardiac striped muscle as in the tortoise heart[2]. It is urged that rhythmic action may originate in muscular tissue independently of the influence of nerve-cells altogether. The question is a very difficult one in the case of the heart. The physiological characters of cardiac muscular fibres are such—in the lower vertebrates at least—that they have been well called "neuro-muscular" (Foster), since in addition to ordinary muscular properties (as seen in skeletal muscle) they possess many properties akin to those exhibited by purely nervous structures. Hence the distinguishing of the functions of cardiac muscular fibres from those of associated nervous structures is very much more difficult than when skeletal muscles are concerned. Differing much both histologically and physiologically from skeletal muscle the cardiac muscle is endowed with properties not possessed in any appreciable degree by the former; the cardiac fibre is probably in some respects a less differentiated form of tissue retaining in a marked degree more of the physiological characters of the original protoplasm, whilst at the same time possessing other properties which have been acquired in consequence of its special mode of functioning and the special nature of its work.

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[1] This *Journal*, Vol. vi., Nos. 1 and 5.

Hence it appears to me to be at least possible that in the mammalian heart the rhythmic contraction originating near the terminations of the great veins may be myogonic in its nature. But in this region nerve-cells are abundant and an intricate arrangement of nerve fibres is present. Moreover it must be remembered that a demonstration of the exhibition of spontaneous rhythmic power in muscular tissue in certain circumstances (more or less abnormal in their character) does not prove the exercise of this spontaneous rhythmic power in the intact normal organ. It might seem remarkable that the muscular tissue should possess a high rhythmic power and never exercise this spontaneous capacity in ordinary life, but it is to be borne in mind that among cold-blooded animals we have abundant evidence of high spontaneous rhythmic power which is constantly in abeyance during normal life; for example in the auricles of all reptiles, amphibians and fishes. In all these the auricular tissue is endowed with a very considerable power of independent rhythmic contraction; in many cases the spontaneous capacity is very high. Notwithstanding this, there can be no doubt that during the normal state of the heart the independent auricular rhythm remains entirely in abeyance, being superseded or led off by the still higher rhythm of the sinus venosus. The auricle beats not by the exercise of its own independent rhythmic power but in obedience to impulses reaching it from the dominant part of the heart, the sinus venosus. Hence the presence in the mammalian heart of muscular fibres with high rhythmic power does not preclude the possibility of the rhythm being in reality a nervous one after all; the muscular rhythm (though apparently superfluous in such circumstances) may be in abeyance, just as the independent auricular rhythm in the lower vertebrates undoubtedly is. The rhythmic tendency of the muscular fibres may be superseded by the higher rhythm originating in the nerve-cells. Analogy indeed would lead one to assume that in normal circumstances the nerve-cells determine the rhythmic discharge. It must be admitted however that it is at present not possible to dissociate with precision the respective actions of these muscular and nervous constituents. Both are in all probability capable of rhythmic discharge; they are so intimately associated both structurally and physiologically that we cannot with confidence discriminate between them as regards the essential nature of the parts they play in the causation of the normal rhythm.

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[1] Sokoloff and Luchsinger. Pflüger's *Archiv*, Vol. XXVI.

[2] Gaskell. This *Journal*, Vol. IV.

All parts of the mammalian heart are endowed with independent rhythmic power.

It is clearly established that in cold-blooded animals the whole of the cardiac tissue possesses a distinct rhythmic tendency, although this property is not at all evenly distributed over the whole organ. Indeed it has been shown in various animals (frog, tortoise, eel) that the sinus venosus, auricle, and ventricle form a descending series as regards their power of exhibiting independent rhythmic contraction. The latent rhythmic power in the ventricle is in many cases (e.g. frog) so low that it is only manifested in certain special circumstances (increased intraventricular pressure, passage of a constant current &c.); hence the ventricle usually stands still and is unable to beat rhythmically when deprived of the impulses that normally pass to it from the rest of the heart and rouse it to action.

In the mammalian heart many facts indicate the possession of independent rhythmic power in all the portions of the organ.

It has long been known that the ventricles can beat regularly for some time after they have been cut away from the auricles. Waller and Reed[1] have lately found that in the cooled excised heart (rabbit, dog) rhythmic contraction goes on for a long time, and the ventricular rhythm is entirely independent of the auricular rhythm; the periodic contraction of the ventricles is not affected by disconnection from the auricles.

Wooldridge[2] performed the experiment of physiologically disconnecting the ventricles from the rest of the heart without causing an actual breach of continuity between the parts; this he did by crushing (by means of an ecraseur) the tissue forming the auriculo-ventricular junction or the lowest part of the auricular tissue close to the auriculo-ventricular groove. Tigerstedt[3] performed an experiment of a similar nature by means of an ingenious apparatus (Atriotom) which enabled him to cut through the auriculo-ventricular junction or the adjacent auricular tissue, and still keep the cut surfaces in apposition, thus preventing any escape of blood. Both these investigators found the ventricles to be capable of exhibiting an independent rhythm; they went on beating regularly though deprived of all structural continuity with the rest of the heart.

I have many times performed the experiment of crushing the auriculo-ventricular junction, with results similar to those of Wooldridge and Tigerstedt. Further, I have in several cases observed that during slowing of the heart's action (cat) caused by vagus stimulation, the slowing has been very much more marked in the auricles than in the ventricles; the rate of ventricular action has sometimes been twice as great as that of the auricular beats. Moreover there sometimes occurs during stimulation of certain vagus branches (cat) a complete standstill of the auricles and great veins while the ventricles go on beating regularly. This phenomenon is far from being a common one; but I have seen it unmistakeably present on several occasions. (To be described in a subsequent paper.) In such instances the ventricular rhythm could not have been dependent on an auricular contraction; it was evidently an independent ventricular rhythm.

The independent ventricular rhythm appears in some conditions at least to be myogonic; it seems to be capable of originating in the muscular tissue and not in nerve-centres.

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[1] *Phil. Trans.* Vol. CLXXVIII. (1887).

[2] *Archiv. f. Anat. u. Physiol.* 1883.

[3] *Archiv. f. Anat. u. Physiol.* 1881.

Many facts support the above conclusion. I have often observed in the dying heart of the kitten that the rhythmic contraction which passes in wave-like fashion over the ventricular tissue begins now at one part, now at another part of the ventricular substance. Moreover I have frequently been able to cause the wave-like contraction to begin at any part simply by employing means to exalt the excitability of the tissue at that part e.g. by the local application of heat. The seat of origin of the rhythmic contraction may in this way be varied at pleasure; the successive contractions begin in the warmed area and thence sweep over the whole of the ventricular substance.

I have on several occasions obtained similar results in the hearts of adult cats poisoned by the injection of a solution of potassium bromide into the blood-vessels. The cardiac contractions under the influence of potash salts become slow and wave-like, the ventricular beats soon become independent of the auricular action; and the origin of the ventricular contraction may often be determined at any point in the ventricular wall—in the way I have mentioned.

Now the ventricles of the cat are certainly not richly supplied with nerve-cells. I have not been able to find any at all in the apical portion. Nevertheless the independent rhythmic action may be made to originate at any part of the apical tissue; and it can hardly be assumed, in defiance of the results of histological examination, that nerve-centres are present at all parts of the wall of the ventricles including their apical portion. Hence it seems very possible that an automatic rhythm may originate in structures other than ventricular nerve-cells, and the only elements in which such a rhythm could be reasonably assigned are the muscular fibres.

Kasem-Beck[1] has recently investigated the occurrence and distribution of nerve-cells in the ventricles of various warm-blooded animals. Examining the hearts of the dog, pig, calf, and sheep, he found that in no case do nerve-cells occur near the apex of the ventricles. The nearest approach he observed was the occurrence of a few nerve-cells at the upper margin of the apical fourth of the ventricular substance. Nerve-cells in the ventricles occur mainly in the basal and middle parts, lying for the most part in the anterior and posterior inter-ventricular furrows and on the left ventricle. Kasem-Beck finds them most abundant in the pig, and most scanty in the dog.

Again, in the intact normally-beating vigorous heart one often finds that the application of a single mechanical stimulus, or the local application of heat to the apex of the ventricles, is followed by the occurrence not simply of a single artificially-excited beat but of a number of greatly accelerated and reversed cardiac beats forming a series of greater or less duration according to the excitability of the tissue and other circumstances. This tends to indicate that one is dealing with a highly rhythmic tissue. And the same assumption is borne out by the behaviour of the ventricular muscle in various conditions to be discussed at a later stage of this paper, its response to minimal and maximal stimuli, the rhythmic rise and fall of its excitability during the occurrence of a periodic series of excitations and its behaviour towards faradic and galvanic currents. In all these respects the mammalian ventricular muscle comports itself in a way essentially similar to what we are familiar with in rhythmic tissues, e.g. in the hearts of cold-blooded animals.

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[1] *Centralblatt f. die Med. Wissenschaften*, No. 42, 1887.

It appears that the cardiac muscle throughout the whole vertebrate series is possessed of certain strongly marked and peculiar characters. Its molecular arrangements are such that any discharge of energy is necessarily a full and maximal discharge; there is no partial or graduated discharge possible at any moment, apart from the influences of nerve control, distension of the cavities, temperature, &c. A discharge of energy induces a period of exhaustion which renders a second discharge impossible until a certain degree of reparation has been attained; in this way the occurrence of a steady and prolonged discharge—like that of complete tetanus in a skeletal muscle—is prevented; hence continued stimulation (e.g. with galvanic currents or weak faradic currents) leads to a series of contractions, and not to a steady tetanus. The phase of exhaustion involved by the occurrence of a beat is gradually recovered from; the amount of energy available for another discharge accumulates; and at the same time the readiness to contract in response to a stimulus increases. At length the process of recovery arrives at such a stage that a discharge of energy can be excited by a minimal stimulus and the discharge so excited is a strong one. If no stimulus is applied when the tissue has recovered sufficiently to be very irritable, it is readily conceivable that a continued rise of excitability or expectancy may in some cases result in a welling over in the form of a spontaneous discharge of energy—in the manifestation of an independent automatic rhythm.

Many features of like character to those obtaining in cardiac muscle have been described by Romanes in the contractile tissues of Medusae.

And the contractile tissues bearing those characters he found to possess distinct rhythmic qualities; they pulsated rhythmically in certain conditions (e.g. when placed in acidulated water) after all the ganglia had been removed.

Further, all those peculiar characters of the cardiac muscle are manifested in identical fashion whether one deals with the basal part of the mammalian ventricles containing nerve-cells, or with the apical portion in which no nerve-cells can be detected. Hence it may be reasonably assumed that the manifestation of all those properties—including the power of automatic rhythm are not necessarily the immediate expression of the functioning of nerve-cells but may be a manifestation of the activity of the muscular fibres themselves.

But, if independent rhythm can be manifested by the muscular tissue of the highly specialised ventricles, may such rhythm not be in even greater degree a property of the muscle of the less highly specialised great veins? It is evident that a consideration of the automatic ventricular rhythm and the evidence in favour of its myogonic nature (in certain circumstances) emphasises the difficulty of determining the precise tissue in which the rhythmic contraction at the venous end of the heart begins. It favours the idea that the rhythm in the latter situation may be myogonic, though it does not at all prove that the rhythm in normal circumstances actually is myogonic.

Though all the parts of the heart are endowed with automatic rhythmic power, the normal action of those parts at the same rate of beat is not due to the existence of an equal rhythmic power in each part; the rhythmic property in the various parts is not equal.

Seeing that all the portions of the heart are possessed of an inherent automatic rhythm, it might be conceived that the identical rhythm seen in all the parts of the intact normal heart might be due to the possession of a similar power of spontaneous rhythm in all the parts, there being in all the parts a correspondence in the processes upon which the spontaneous rhythm of each depends. The rhythmic processes in veins, auricles, and ventricles might be so timed that all these parts would beat at the same rate per minute, like a number of clocks ticking at the same rate side by side.

A good instance of such an arrangement is to be seen in the eel's heart, where the right and left ostial parts of the sinus beat with an identical rhythm, apparently in consequence of a precise identity in the time relations of the tissue changes underlying the rhythmic discharge. The simultaneity of contraction in the right and left ostials often continues after these parts are completely separated from one another and from all the other parts of the heart.

But in the mammalian heart it at once becomes evident on examination that there is a very close connection between the various parts. Contraction of one part—in whatever way excited—determines the occurrence of contraction in all parts of the organ. Contraction then in the great veins necessarily leads to the manifestation of a beat in auricles and ventricles; and conversely a ventricular beat excited in a quiescent heart induces a contraction in the auricles and great veins. Contraction excited in one part at any moment involves all the other parts, even though they have very recently contracted and are not yet prepared to discharge another beat in virtue of the spontaneous rhythmic power inherent in them.

It is evident then that if one portion of the heart possesses a higher power of spontaneous rhythm than the rest of the organ, the rhythm of the former will supersede the inherent rhythm of the other parts and determine the rate of contraction in the whole organ.

Such an arrangement we are familiar with in the hearts of cold-blooded animals, where the dominant part is the sinus venosus—its rapid rhythm superseding the slower inherent rhythm of auricle and ventricle and determining the rate at which the whole heart beats.

In the mammal it is very much more difficult to compare the spontaneous rhythmic power of the different parts of the heart than in cold-blooded animals. For the experiments by section, ligature, and clamping which have proved so instructive in the latter are not applicable in the same way in the hearts of warm-blooded animals; the escape of blood from the cavities of the organ and the interference with the vascular supply of the cardiac tissue prove grave difficulties in the latter.

Nevertheless there is a considerable amount of evidence going to prove that the power of spontaneous rhythm inherent in the cardiac tissue is not equally distributed over the whole organ; that the spontaneous rhythmic tendency is indeed markedly different in degree in the various parts of the mammalian heart.

The independent ventricular rhythm observed by Wooldridge and by Tigerstedt was much slower than the rhythm of the auricles, much slower than the rhythm of the intact heart. It may of course be argued that the independent ventricular rhythm described by these observers might have been abnormally slowed in consequence of the operative procedure adopted. By the application of Wooldridge's method the blood-flow through the heart was temporarily arrested, while the ecraseur was being lightened, and some of the coronary vessels may have been injured. In Tigerstedt's experiments the inter-auricular septum was cut through and a certain derangement of the circulation necessarily resulted; at the same time a constant though gradual fall in the arterial blood-pressure was recorded. Further, it may be urged that the ventricles would be more ready to suffer from an interference with their blood-supply than would the auricles, since as has long been known, the ventricles in the ordinary process of death lose their excitability more readily than the auricles. A depression of the ventricular excitability thus brought about would of course involve a slowing of their inherent rhythm, and the diminished ventricular rate (as compared with that of the rest of the heart) might be thus accounted for. But, on the other hand, it must be remarked that it is the auricular branches of the coronary arteries that are mainly interfered with in the experiments of both these investigators.

Further there is often to be seen during certain phases of inhibition what clearly seems to be an independent ventricular rhythm; this rhythm is very markedly slower than the rate of the ventricles when beating in sequence to the rest of the heart. And here is no special interference with the ventricular blood-supply; probably only a temporary and comparatively slight fall affecting the whole heart.

Moreover I have often seen the ventricular contraction preceding the auricular contraction for one or more beats under inhibitory influences (Pl. IV. Fig. 10).

Again, there is a considerable amount of evidence showing that the inherent rhythmic power of the venous end of the heart is decidedly higher than the inherent rhythmic power of the ventricles. Stimulating agents locally applied to the cardiac tissue can be shown to increase the heart's rate much more readily and much more strikingly when applied to the venous end of the organ than when applied to the ventricles. For example the application of slight heat locally to the terminal part of the vena cava superior gives a very marked acceleration in the rhythm of the whole heart (Pl. III. Fig. 6 and IV. Fig. 9). A similar slight local heating of the ventricle apex or any part of the ventricular substance gives no change in the cardiac rate. And so with weak constant and faradic currents; applied to the venous terminations they exert a very marked accelerating influence on the action of the whole organ; applied to the ventricles they do not (if sufficiently weak) cause any change in the cardiac rhythm. It is indeed true that strong local heat applied to any part of the ventricular substance may induce a temporary acceleration of the heart's rhythm, the sequence of contraction being at the same time reversed; the ventricles beat before the auricles and the venous terminations. But comparatively strong heating is necessary for the production of such a result; the slight heat readily effective when applied to the venous terminations, is usually quite inoperative when applied to the ventricular substance.

A similar rule prevails with regard to constant currents, though *strong* constant as well as moderate faradic currents are not suitable for application to the ventricles in regard to this question, as they produce an entirely different and special result (fibrillar contraction, delirium, &c.) which does not specially concern the point now under consideration.

(The effects mentioned are all to be observed in animals in which inhibitory influences have been paralysed by atropine as well as in unpoisoned animals.) These results in the mammalian heart are essentially similar to what we are familiar with in the hearts of cold-blooded animals. In them (e.g. frog, tortoise, eel, &c.) the application of slight heat, very weak faradic, or constant currents to the sinus venosus, gives a marked acceleration in the rhythm of the whole organ; a similar application to the ventricle has no effect on the rhythm. And it can be demonstrated by section experiments that the sinus is undoubtedly the part of the heart endowed with the highest power of spontaneous rhythm in those animals.

Further, the venous terminations are in the mammalian heart the parts that usually pulsate longest in the dying heart; their action may often be seen to be quite regular when all the other parts of the heart have entirely ceased to beat and even when they have become insensitive to direct stimulation. This state of things quite corresponds with the great vitality of the sinus venosus in cold-blooded animals.

It is apparent then that the great relative sensitiveness of the venous terminations to stimulating influences (heat, electrical currents, &c.), and their high vitality plainly indicate the possession by them of a very high rhythmic power—a spontaneous rhythm higher than that present in any of the other parts of the heart.

There is little room for doubt that the rhythm originating in the terminal parts of the great veins or at the junction of the great veins with the auricles is a rhythm which dominates the whole heart and determines the rate of its action. For the contraction initiated in this region spreads over the entire organ determining a discharge of energy throughout the cardiac musculature. The beats originating in or near the venous terminations lead off the contractions of the auricles and ventricles; these parts act in sequence to the initial contraction in the great veins. Although the ventricles can be shown in certain circumstances to manifest an independent rhythm of their own, and so would be able to beat on their own account apart from the occurrence of any antecedent contraction in other parts, yet the series of ventricular beats so produced would be at a much slower rate (caeteris paribus) than those exhibited by an intact heart. And the same may with much probability be asserted of the auricular tissue proper.

It is evident then that the normal rhythm seen in the ventricles of an intact heart depends not on the power of spontaneous action inherent in the ventricular muscle, but on the propagation to the ventricles of the more rapid series of contractions originating at the venous end of the heart and reaching the ventricles through the mediation of the auricles. The parts at the venous end of the heart are prepotent with regard to both the auricular tissue proper and the ventricles.

The inherent rhythmic power latent in the auricles and ventricles may in these circumstances seem somewhat superfluous. But we know for certain that such exists in cold-blooded animals; that the auricles for example possess a considerable power of independent spontaneous activity, but that this rhythm is superseded and kept in abeyance by the higher rhythm of the sinus, just as the automatic respiratory rhythm in man can at any time be temporarily superseded by a more rapid voluntary rhythm.

The causes determining the rhythm of the intact heart are to be sought for at the venous end of the organ, since here is located the dominant rhythm. It can be shown that the contraction arising here is not essentially dependent on a distension of the parts with blood or a stimulation by the presence of blood in their cavities; the beating goes on quite regularly for a considerable length of time when the cavities are empty and collapsed. Hence the view advocated by Haller, and by many since his time, that contact with the contained blood is the determining cause of the heart's rhythm cannot be regarded as adequately meeting the case. And the same may be said of the suggestion of Brücke, that the rhythm is due to the conditions of the blood supply through the coronary vessels. Also of the views of Brown-Sequard, Lanneloque, Senac and various others.

The view propounded by Paget, ascribing the cardiac beat to a rhythmic mode of nutrition, called attention to the truth that the essential cause of the heart's rhythm is to be sought in the molecular changes occurring deep in the cardiac tissue.

On a reversed mode of contraction of the Heart.

The application of a single stimulus of any kind (electrical, mechanical, or thermal) to any portion of the cardiac tissue during the diastolic period usually leads to a contraction of the whole organ—great veins, auricles and ventricles all participating in the beat. The order of contraction varies as the stimulus is applied to one part of the heart or another. When the excitation is brought to bear on the terminal portion of one of the great veins (e. g. superior vena cava) the resulting contraction exhibits the same general order of sequence as in the normal spontaneous beat; the stimulated vein contracts first, then the auricles (and probably the terminal portions of the other veins) and then the ventricles. (The difference between such a beat and a normal one is in the precedence of the stimulated vein over the other venous terminations.)

When the stimulus is applied to the auricles, the beat shows a somewhat different sequence. The auricles contract first, and then the great veins on the one hand and the ventricles on the other.

Again, when the stimulus acts directly on the ventricles, there is a complete reversal of the order in which the different parts of the heart normally contract. The ventricles contract first, then the auricles and then the great veins.

The heart then can readily be artificially excited to execute beats either in an approximately normal or in a completely reversed fashion. The reversal caused by the application of a single induction shock to the ventricles during the period of diastole usually affects one beat only, the beat excited by the stimulus. The normal order is then immediately re-asserted. But in a very excitable heart, a mechanical or thermal stimulation or even a single electrical stimulation of the ventricles often leads to a reversal persisting over several beats; a number of reversed contractions may occur before the normal sequence is restored. And in any heart a reversed form of beat may be kept up by applying to the ventricles a series of single stimulations of somewhat greater rapidity than the normal spontaneous rhythm. By such means the normal spontaneous rhythm is not allowed to come into play; the contraction of the heart is artificially excited before the organ is prepared to emit a spontaneous discharge of energy. The normal rhythm is superseded by a more rapid artificial rhythm.

During the period of cardiac standstill resulting from stimulation of the vagus nerve a reversed form of contraction may be easily induced;

a single excitation (e.g. an induction shock) of the ventricles gives a single reversed beat, and a series of excitations (e.g. a series of induction shocks at the rate of say 2 per second) causes a series of reversed beats. Reversed contractions sometimes occur spontaneously at certain phases of vagus influence (Pl. IV. Fig. 10).

It is a matter of considerable interest and importance to note the influence exerted on the circulation of the blood by such a reversed mode of cardiac action. It has a practical bearing on the question of artificial excitation of the human heart by electric shocks during certain forms of chloroform syncope and allied conditions. For the passage of shocks through the heart in man might excite either the normal or the reversed sequence according as whether the auricles or the ventricles were mainly affected by the current, and according to the relative excitability of those parts obtaining in the special conditions in question. Would a reversed mode of contraction be of service in discharging the contents of the heart and in raising the blood-pressure?

In the eel I found that a reversal of the normal order of cardiac sequence when kept up for some time was attended by a marked obstruction of the circulation; the sinus and auricle became gorged with blood, and their action was almost annulled.

In mammals (cat and rabbit) I have made a considerable number of experiments on this point. I find that, when the heart has been brought to a standstill and the blood-pressure greatly reduced by vagus stimulation, a series of artificially excited beats is attended by a marked improvement in the condition of the heart and a considerable rise in the blood-pressure, though the pressure never attains the normal height in these circumstances—as far as I have seen.

On the sequence of contraction in the different chambers of the heart.

There has now to be considered the mode in which the contraction originating in the parts possessed of the highest rhythmic power (the terminal regions of the great veins) is propagated over the less highly rhythmic portions of the organ—the auricles proper and the ventricles.

It has been recently urged by Gaskell[1] that in the heart of the tortoise the contraction is propagated over the heart by muscular conduction—simply as a wave sweeping along the muscular tissue. In the hearts of all cold-blooded animals examined there is complete histological continuity evident between the muscle of the various parts.

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[1] This *Journal, loc. cit.*

And in the eel's heart I have described a form of muscular connection between the ventricle and the rest of the heart which accords remarkably with the muscular conduction hypothesis as applied to the explanation of the various phenomena (blocking, &c.) which are observable in this region[1]. Moreover there is abundant evidence that the larger intra-cardiac nerves and the ganglia are not at all necessary for the efficient propagation of the contraction. But with the finest nerve filaments that ramify among the muscular fibres the case is entirely different. It seems to me that in the hearts of cold-blooded animals it is impossible rigidly to exclude the possibility of an important conducting function being discharged by the fine nerve fibres that run in the muscular substance. It seems to be impossible at present to dissever with certainty the parts played by the muscular and nervous elements respectively.

In the mammalian heart the structural connection of the great veins with the auricles is essentially similar to what obtains in cold-blooded animals, inasmuch as there is muscular continuity between the venous and auricular walls; the problem as to the mode of propagation may be said to stand on the same footing as in the lower vertebrates. But the question as to how the contraction is propagated from auricles to ventricles, stands on an entirely different basis, inasmuch as the structural relations of these parts to one another are entirely different. Instead of complete muscular continuity throughout the heart there occurs in the mammalian heart a distinct break—a distinct interval—between the muscle of the auricles and the muscle of the ventricles. The auricular fibres and the ventricular fibres belong to systems of their own, and are separated by a considerable amount of connective tissue at the auriculo-ventricular junction. The part where the auricular and the ventricular muscular fibres are most closely approximated is at the bases of the auriculo-ventricular valves, but even in that situation there is a distinct want of continuity, a well-marked separation between the auricular and ventricular systems.

It is evident then that the whole question of propagation from auricles to ventricles is in mammals on a footing quite different to the similar question in cold-blooded animals. Clearly the propagation in mammals cannot be due to simple muscular conduction—to the passage of a wave of muscular contraction from one part to the other.

There are various conceivable modes in which the transmission of the contraction might be effected in mammals. For example—

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[1] This *Journal*, Vol. VI.

(*a*) The sequence of the ventricles might depend on their being suddenly distended with blood forced into them by contraction of the auricles; stimulated by this sudden rise of pressure in their cavities the ventricles would contract—their beat thus occurring in sequence to the auricular beat. And there is little doubt that the ventricles are decidedly affected by sudden and considerable changes of pressure in their cavities.

There is a considerable amount of evidence, however, to prove that the propulsion of blood into the ventricles at each auricular beat is often insufficient—in the absence of other causes of propagation—to ensure the ventricular sequence.

Some evidence of this kind is to be obtained from the experiments of Wooldridge and of Tigerstedt. After physiologically disconnecting the ventricles from the auricles (by crushing or cutting the auriculo-ventricular junction) without materially interfering with the flow of blood through the cavities of the heart, these observers found that the ventricles exhibited a rhythmic action quite independent of the auricular action; a ventricular beat did not follow each auricular beat as in the normal heart. The sequence of ventricles upon auricles was abolished. The sudden distension of the ventricles with blood forced into them by the auricular contraction was obviously insufficient to determine a ventricular beat. Of course it may be doubted whether the ventricular tissue was quite in its normal state of excitability; a depression of the ventricular irritability may have resulted from the operative interference with the organ and hence there might have been an abnormal sluggishness in responding to the changes in intraventricular pressure caused by the auricular beats. It seems hardly probable that a change in the ventricular excitability could have so quickly occurred in such a degree as to give the result referred to; for one often sees that in the intact heart the ventricular sequence persists with complete regularity even after the ventricles have suffered a very decided diminution of their irritability. Hence it would seem probable that in the intact heart other factors are concerned beyond the changes in intra-ventricular pressure determined by the auricular beat.

Again, I have often observed instances where auricular contractions failed to cause responsive ventricular beats, and yet these auricular contractions were of very considerable strength—strong enough indeed to cause visible dilatation of the ventricles from the rise of intraventricular pressure caused by each auricular beat. Such instances are often observable when the heart has been stopped by stimulation of inhibitory structures and has just recommenced beating; occasionally also before inhibition has become fully established. The auricles sometimes give one or more beats that are not propagated to the ventricles though blood is forced into the ventricles at each auricular beat (Pl. IV· Fig. 11). In similar conditions the ventricles sometimes give only one beat in response to every second or third auricular beat.

Further, there occur cases in which stimulation of inhibitory structures (vagus nerve or inhibitory area) causes ventricular standstill while the auricles go on beating. And in these cases, the direct excitability of the ventricles, as tested by single induction shocks applied to their surface, seemed unimpaired. Moreover, mere weakness of the auricular beats would not account for the non-response of the ventricles; for very much weaker auricular beats than those observed in the above-mentioned cases are quite sufficient, in the uninhibited heart, to determine the occurrence of responsive ventricular contractions. The failure of ventricular sequence was in all probability due to an interference with a mechanism of propagation quite different from the pressure changes caused by the auricular beats.

Further, contraction can be propagated from auricles to ventricles when there can be no question of an intra-ventricular rise of pressure being caused by the auricular beat.

This fact can readily be demonstrated in the case of the empty heart when precautions have been taken to prevent the entrance of air into the cavities. This is easily done by clamping all the great veins on both sides of the heart. After the heart has discharged its contents and become empty, I have often watched the sequence of the contraction both with the heart in situ and after excision. The normal spontaneous sequence can be seen to continue with complete regularity for a considerable period, often for several minutes. Moreover when the rate of action has become somewhat slowed it can be shown that artificially-excited contraction of the auricles is propagated to the ventricles, and artificially-excited beats of the ventricles awake responsive auricular contractions. Contraction can thus be readily propagated across the auriculo-ventricular junction in both directions, in the normal direction or the opposite. Propagation sometimes fails in one direction while it can still occur in the other direction; sometimes an artificially-excited ventricular beat is transmitted to the auricles while an artificially-excited auricular contraction is not propagated to the ventricles; this, however, appears in many cases at least to be due to a depressed ventricular excitability.

It is obvious then that though a strong auricular beat might possibly lead to the occurrence of a ventricular beat in consequence of a sudden distension of the ventricular cavities, such a mode of sequence is by no means an essential one.

For the regular ordinary sequence occurs when no such cause is operative (e.g. in the empty heart); and the sequence is often seen to fail when the above-mentioned cause is still present.

It is plain that there is some other mode of propagating contraction from auricles to ventricles and vice versa.

(*b*) It might be conceived that the electrical variation accompanying the auricular beat might act as a stimulus to the neighbouring ventricular tissue—especially in the case of the empty heart when there is no mass of blood present to short-circuit the current. There is no evidence in favour of such a hypothesis, and various considerations are opposed to it—the weakness of the auricular current, the fact that the sequence persists when means are taken to short-circuit the current in the empty heart, e.g. when the heart is immersed in (warm) mercury.

(*c*) The cause of the ventricular sequence might be sought in the conditions of the mechanical connection between the auricles and the ventricles.

When the ventricles of a still living and excitable heart have been severed from the rest of the organ by a transverse section made just below the level of the auriculo-ventricular valves, it can easily be shown that a slight but sudden pulling of the cut end of one of the chordae tendineae when the ventricles are quiescent frequently causes a ventricular beat. It is probable that any sudden increase in the tension of the chordae tendineae in the intact heart would lead to the occurrence of a ventricular contraction. Now it has long been known that some of the auricular muscular fibres pass into the flaps of the auriculo-ventricular valves constituting the radial fibres of these structures. And the chordae tendineae are attached to the ventricular aspect of the flaps. Hence as the fibres of the valve no doubt contract with the rest of the auricular muscle, it is conceivable that at each auricular beat a sudden increase of tension might be communicated through the valves to their attached chordae, and in this way a ventricular contraction might possibly be excited. For it must be borne in mind that the ventricles are very easily caused to contract towards the end of the diastolic pause. Their excitability differs widely from that of ordinary skeletal muscle in this respect that while the excitability of the latter remains practically constant over considerable periods, that of the ventricles on the other hand is constantly passing through cyclical changes, falling at each beat, and rising again through the diastolic pause until it has reached its maximum or until another beat has occurred. Hence the stimulus required to excite a ventricular contraction after the occurrence of a pause of approximately normal duration is not necessarily a strong one; a very weak stimulus is effective.

I have on many occasions performed an experiment bearing on this question—on the possibility of the ventricular sequence being dependent on the above-mentioned mechanical cause. The experiment consists in severing the chordae tendineae by making a section across the upper part of the ventricles so as to leave say the upper third of the ventricles in connection with the auricles. The chordae are thus completely divided; their cut ends can be seen hanging loose in the ventricular cavities. In the case of a vigorous heart I have often seen the contraction regularly propagated from the auricles to the upper portion of the ventricles still in connection with the auricles; the sequence continued unimpaired for a considerable period of time. Moreover it can be shown that artificially-excited contraction of the auricles can be propagated to the ventricles ; and similarly an artificially-excited ventricular beat can be transmitted to the auricles in favourable circumstances. Hence it is obvious that propagation of the contraction can be conducted across the auriculo-ventricular junction in both directions, in normal sequence from auricles to ventricles, and in reversed fashion from ventricles to auricles without the mediation of the tendinous connections between the ventricular walls and the valvular arrangements at all.

In some instances the above-mentioned section-experiment fails; the auricular contraction is not propagated to the still-attached portion of the ventricles. When the heart is not a strong and vigorous one, or when the ventricular tissue has been subjected to compression or other injurious influence there is usually a failure in the sequence of the contraction. The experiment is of course in any case a very rough one and the heart is necessarily placed in very abnormal conditions, but still a positive result is, it seems to me, of very considerable significance. The fact that the contraction is often seen to be propagated with great regularity not only in the absence of the mechanical connections established by the chordae tendineae but in unfavourable circumstances generally (want of blood-supply, depression of temperature, &c.) is clearly one of much importance. A negative result of the experiment, on the other hand, would not have carried much weight as it might readily have been accounted for by a depression in the excitability of the cardiac tissues.

A similar experiment can be performed in a more satisfactory way—by feeding the cardiac tissue with a stream of arterial blood at approximately normal temperature and pressure through the coronary arteries, and then making a section across the upper part of the ventricles.

I have on several occasions performed such an experiment; the cavities of the heart were empty, and an artificial circulation was established through the coronary vessels. After the ventricles had been cut across in the way already mentioned and the chordae tendineae severed, the propagation of contraction from the auricles to the attached (basal) portion of the ventricles was quite unimpaired. The basal part of the ventricular substance contracted regularly in sequence to each auricular beat. I have watched such a sequence over a period of more than half an hour, the rate of cardiac beat being for the greater part of the time about 120. Whilst this condition obtained, I found that a moderate acceleration of the auricular rhythm (induced by direct stimulation of the auricular surface) was accompanied by a corresponding acceleration of the ventricular rhythm, the ventricular beats following the auricular in regular sequence, and rising and falling pari passu with the latter. The transmission of contraction from auricles to ventricles was evidently quite active, and this in a heart the cavities of which were empty of blood and the chordae tendineae severed.

It is evidently impossible to account for the sequence of the ventricular beat on the auricular beat upon purely physical grounds.

It would seem to be clear that the propagation of the contraction from auricles to ventricles is effected through the nerves that pass between these parts.

When the nervous connections are destroyed as (in Wooldridge and Tigerstedt's experiments) when the tissues forming the auriculo-ventricular junction are crushed or cut through, the transmission of the contraction is interrupted; the sequence of the ventricular beat on a preceding auricular beat is lost. On the other hand, when the nervous connections remain intact and the muscular excitability of the heart is not materially impaired, the contraction can pass readily from auricles to ventricles, notwithstanding many changes in the state of the organ, e.g. an absence of the normal contents of the cavities as in the empty heart, an interference with the mechanical connections of the parts as when the chordae tendineae are cut through, &c.

Moreover, I shall have to describe in a subsequent paper certain cases of nervous interference with the propagation of contraction from auricles to ventricles; forms of interference which would be very difficult to explain apart from the existence of a nervous mechanism of propagation.

It is impossible at present to define the precise form of nervous mechanism concerned in the maintenance of the ventricular sequence—in the transmission of the contraction from auricles to ventricles. The nervous arrangements may indeed be found to assume a peculiar type.

Some hypothetical nervous arrangements may be adverted to—

(1) It might be conceived that if nerve-cells are always concerned in the auricular contraction, motor fibres issuing from these cells might pass to the ventricles as well as to the auricles; and hence a motor incitation would be sent from the nerve centres to both auricles and ventricles.

But, with a simple arrangement of this sort, it is difficult to explain the pause between the auricular beat and the ventricular beat; the contraction of auricles and ventricles ought to be practically simultaneous.

(2) It might be conceived that afferent impulses arising in connection with the contraction of the auricular muscle may pass to a nerve centre, or to nerve centres from which efferent impulses proceed to the ventricular muscle.

There is no evidence to prove the existence of such a centre in the ventricles however. The nerve-cells, as far as they have been observed to occur at all, are superficially situated in the ventricles, and paralysis of them by the application of strong ammonia to the ventricular surface does not interfere with the regular sequence.

And even if the hypothetical nerve centre referred to be assumed to exist, not in the ventricles but in the auricles or in the auriculo-ventricular groove (where nerve-cells and ganglia abound), the facts of reversed contraction of the heart are still to be accounted for. Propagation of contraction from ventricles to auricles involves the conception of a second system of fibres, afferent fibres from the ventricular substance to the hypothetical nerve centre, and efferent fibres from that centre to the auricular muscle—either directly to the muscular tissue or primarily to a nervous plexus in the auricular wall.

Moreover the character of the auricular contraction opposes the idea of its being due to the influence of a motor centre sending out simultaneous impulses to all the muscular fibres. For whenever the rate of propagation is markedly slowed, the progressive nature of the auricular contraction becomes very plainly evident. There is no simultaneous action of the whole auricular wall, but a wave of contraction sweeping over the tissue from the endings of the great veins. And such a mode of contraction is often quite patent when there is no reason to believe that the action of the heart has been deranged or indeed essentially altered—except in so far as the rate of propagation is slowed, e.g. under the influence of cold, or of various drugs.

Moreover, when reversed contraction occurs it can sometimes be distinctly seen that the contraction begins at the auriculo-ventricular groove and thence spreads over the auricular walls.

(3) Nerve fibres connected with the auricular muscle may pass to the ventricles, probably being intermediately connected with nerve-cells near the auriculo-ventricular junction.

It is possible that there is a simple fundamental mechanism of nervous connection between all parts of the heart; an extensive plexus of nerve fibres throughout the whole of the cardiac wall, perhaps with nerve-cells interposed at certain parts such as the auriculo-ventricular junction. Such a nerve plexus would stand in very close relation with the muscular fibres at all parts, and would be capable of conducting with more or less readiness in any direction. The nerve-cells are probably concerned in bringing the extra-cardiac nerves into close relation with the mechanism of contraction.

What is the nature of the nerve influence that determines the ventricular sequence?

Is it a constant influence, or an intermittent discharge?

The ventricles we have seen are capable of independent rhythmic action. This independent rhythm can be accelerated by influences of a constant nature, e.g. galvanic currents. Hence, it is conceivable that a constant nervous influence from the basal parts of the heart acting on the ventricles might cause the ventricular rhythm to be of the same rapidity as that of the remainder of the heart. But the important fact that an auricular contraction excited at any phase of the cardiac cycle induces a ventricular beat controverts the idea just stated, and indicates that the influence reaching the ventricles from the auricles is of the nature of an intermittent excitation. And the facts of reversed contraction have a similar bearing.

In the case of the cat's heart there is no evidence to show that contraction can be propagated from the great veins to the ventricles without a contraction of intervening auricular tissue.

Contraction may indeed pass from the venous terminations (e.g. the end of the superior cava, in the cat) to the ventricles without involving the whole extent of the auricular walls. In such cases the contraction usually passes along the dorsal aspect of the auricles, without passing over the lateral or anterior aspects at all. The auricular surface, however, over which the contraction passes always forms an unbroken track from the venous termination to the auriculo-ventricular junction. The contraction never seems to leap over any portion of the auricular wall in its course; it never seems to reach the auriculo-ventricular junction except by traversing the auricular tissue in its progress.

The dorsal region of the auricles is not the only part concerned in the propagation of contraction to the ventricles.

The ventricular sequence continues unimpaired when the dorsal auricular wall has been cut across, or better, crushed near the auriculo-ventricular groove, or when the auriculo-ventricular junction has been crushed in this region. The contraction must then be transmitted through the connection of the remaining parts of the auricles with the ventricular tissue.

The dorsal region of the auricles is the part in which the power of propagation is longest retained in the dying heart. It appears to resemble in some of its properties, as well as in its position, the basal wall of the auricle or auricles in the hearts of different cold-blooded animals (eel, frog, tortoise, snake, &c.).

In the rabbit's heart the structural relation of the terminal parts of the great veins to the ventricles is different from what obtains in the cat's heart. In this animal I have sometimes observed that, in a dying heart, an artificially-excited ventricular contraction passes over the venous terminations before it appears in the auricles at all. Such a sequence may at times be observed with great distinctness, the parts beating in the following order—ventricles, great veins, auricles.

When a ventricular beat occurs in sequence to an auricular beat, the strength of the former does not appear to be at all influenced in any direct fashion by the strength of the latter. (It is of course well known that the auricular beat in the intact heart can indirectly influence the ventricular beat, by determining in some measure the distension of the ventricular cavities with blood prior to the contraction of the ventricular muscle.)

An auricular contraction appears to induce the occurrence of a ventricular contraction—to determine its exhibition at a certain moment and not to influence its strength directly.

The time at which the ventricles contract in the intact heart is directly determined by impulses reaching them from the auricles; the strength with which the ventricles contract is directly dependent on the conditions obtaining within the ventricles themselves (e.g. the amount of explosive material ready, the physical conditions of distension, temperature, &c.). A weak auricular contraction does not necessarily cause a weak ventricular discharge; there is no necessary relation between the contraction force manifested in the one and the other; the contraction is always maximal.

Propagation of contraction within the auricles.

There has to be considered the question of propagation of the contraction process within the substance of the auricles and ventricles.

In the auricles the general phenomena bearing on this question are much of the same character as those described in cold-blooded animals.

The auricles do not contract simultaneously at all parts; the process of contraction is a progressive one, beginning at the terminations of the great veins and thence sweeping over the whole auricular wall. Similarly, when the auricles are artificially excited to contract by the application of a single stimulus (e.g. an induction shock) applied to some limited area of the auricular wall, the resulting beat does not assume the form of a simultaneous contraction of the whole auricular muscle, but a contraction originating in the stimulated area and thence extending in all directions over the whole of both auricles. These facts are very apparent in a heart which is acting somewhat sluggishly from any cause (e.g. cooling). Moreover, when a reversed beat of the heart is excited (by applying a single stimulus to the ventricles), the auricular contraction may often be very distinctly seen to be a progressive one, beginning at the lower margin of the auricles at the auriculo-ventricular junction, and thence travelling upwards to the great veins.

Hence it would seem that the auricular beat is not excited through the instrumentality of a nerve centre sending out simultaneous impulses to all parts of the auricular muscle.

The passage of a contraction through the auricular wall seems to occur quite independently of the larger nerves. This is indicated by the fact that the contraction can travel over a zig-zag shaped isthmus of tissue made by several overlapping incisions; it matters not in what direction the incisions are carried. Moreover, the free application of strong ammonia to all the nerves visible with the naked eye or with a weak lens, does not arrest the transmission of the contraction (either in the auricles or the ventricles).

In a vigorous intact heart well filled with blood in situ, it can often be seen that, if one of the auricular appendices is physiologically disconnected from the rest of the auricle by crushing, the appendix so treated often goes on beating rhythmically and keeps time with the rest of the auricular wall. And this happens in circumstances where we must regard all vital connection between the muscle of the appendix and the remaining auricular muscle as destroyed—by forcible temporary compression with a clamp. The correspondence of the rhythm, exhibited by the appendix with that of the auricular wall generally, appears to be dependent on the fact that increased tension within the appendix caused by the beginning of the auricular contraction, stimulates the appendix and determines the occurrence of its beat. Such a reason, though explaining the phenomenon just mentioned, would not of course account for all the phenomena of propagation in the auricles; since propagation occurs perfectly well in an empty heart. It is due to the passage of the contraction process over the auricular wall either as a simple muscle wave, or as an excitation travelling along a nervous network intimately associated with the muscular fibres.

EXPLANATION OF FIGURES.

All the tracings read from left to right.

The marks on the time tracings in all cases indicate half-seconds.

Plate III.

Fig. 1. Shows the contractions resulting from the alternate application of weak and strong shocks to the quiescent ventricles of an excised heart (cat). The record was obtained by means of a light lever resting on the ventricles. It is seen that the contraction force does not vary according to the strength of the stimulus, but is always maximal. The curves marked *W* and *S* indicate the results of weak and strong shocks respectively.

Fig. 2. Groups of contractions excited by weak (*W*) and strong (*S*) shocks in ventricles of a heart (cat) rendered quiescent by vagus stimulation.

Weak shocks obtained with secondary coil at 14 cm.

Strong ,, ,, ,, ,, ,, 4 cm.

Fig. 3. Groups of contractions excited by weak (*W*) and strong (*S*) shocks applied to the ventricles of a heart (cat) brought to a standstill by vagus stimulation. Strength of shocks as in case of Fig. 2.

Fig. 4. Same conditions as Fig. 3, excepting that the strength of the excitation was more frequently varied, pairs of weak shocks alternating with pairs of strong shocks. The same general result is seen.

Fig. 5. Tracing from ventricles (cat). A succession of induction shocks applied to the ventricular surface beginning at the point marked ↓ and ending at the point marked ↑. The shocks were sent in with varying frequency and a series of contractions of similar frequency was excited. It is seen that the markedly accelerated contractions are greatly diminished in force; the strength of each beat varies according to the degree in which reparation from the exhausting effect of a preceding contraction has occurred.

Fig. 6. Shows the acceleration induced by the application of heat to the terminal part of the vena cava superior (cat). The phase of acceleration is followed by a "compensatory pause" succeeded by a large ventricular beat.

PLATE IV.

Fig. 7. Tracing from cat's heart showing a marked increase in the size of the ventricular beats attendant on a simple slowing of the rhythm by weak vagus stimulation. Later the beats become weakened by stronger vagus influence.

Fig. 8. Shows a marked increase in the force of the ventricular beats accompanying a simple slowing of the rate of beat—under weak vagus influence (cat).

Fig. 9. Tracing from cat's heart; shows the acceleration resulting from the application of heat to the terminal (ostial) part of the vena cava superior. The acceleration is accompanied by a marked diminution in the force of the individual beats.

Fig. 10. Shows the occurrence of the reversed mode of contraction, in a heart (cat) under inhibitory influence. After the cessation of the stimulating current applied to the vagus nerve (indicated by movement of signal) the first recommencing beat is a reversed one.

Several ventricular beats occur without any auricular beats—not only without any auricular contractions being indicated on the tracing, but without any contraction which could be detected by the careful direct observation of the parts at the time.

Fig. 11. In the early part of the tracing, under vagus influence, two strong auricular beats occur without any ventricular contraction at all. The heart (cat) was well filled with blood, and the auricular contraction pumped a considerable amount of blood into the ventricles without exciting a beat in the latter. The more rapid series of ventricular contractions occurring after a pause is due to the application of direct stimuli to the ventricular surface.

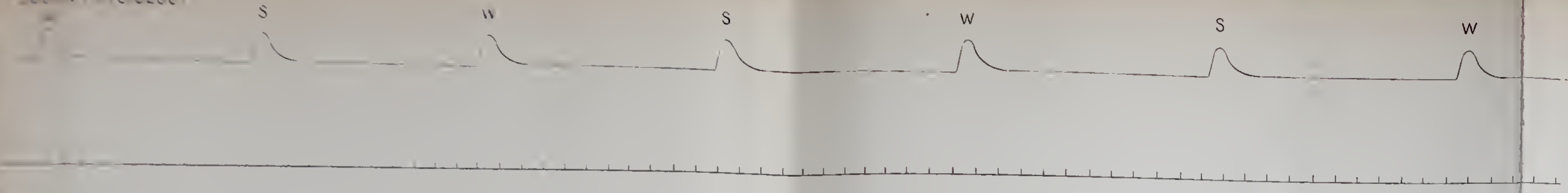
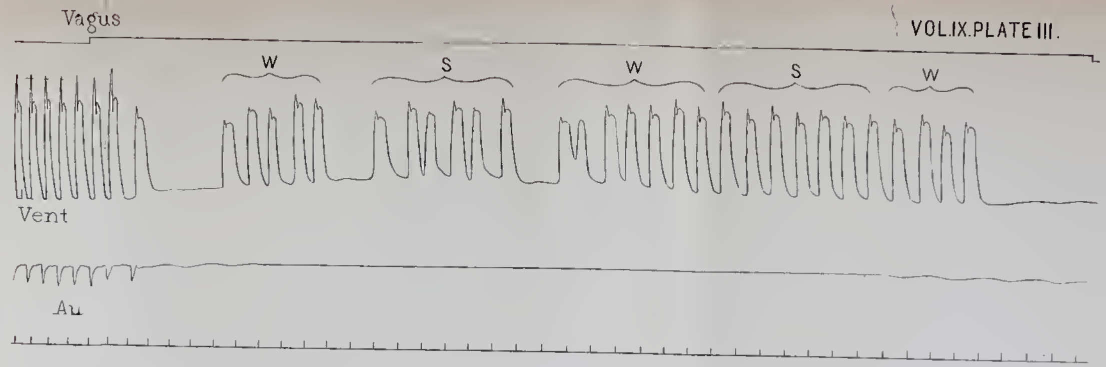


Fig. 1.



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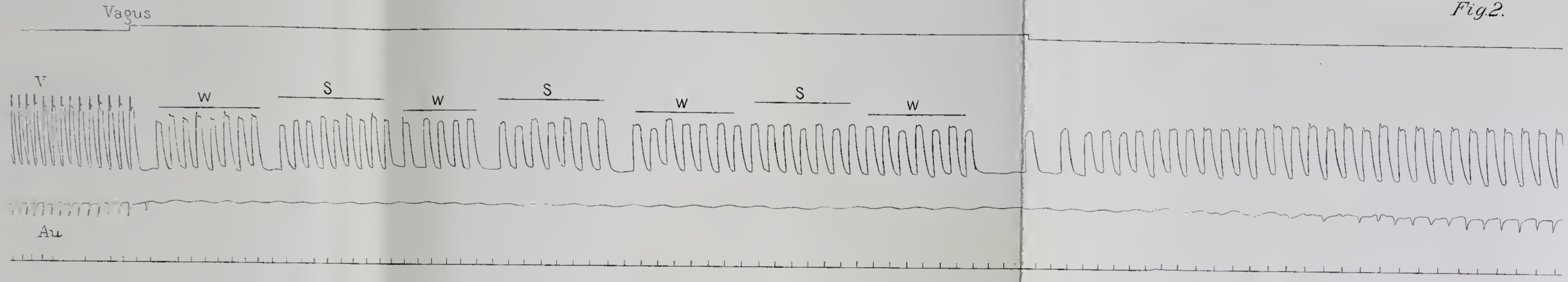

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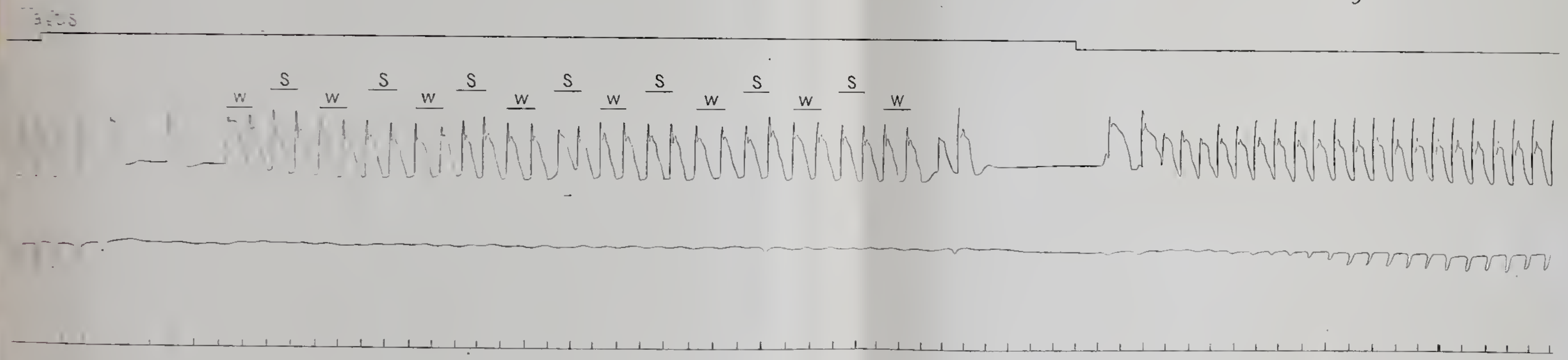

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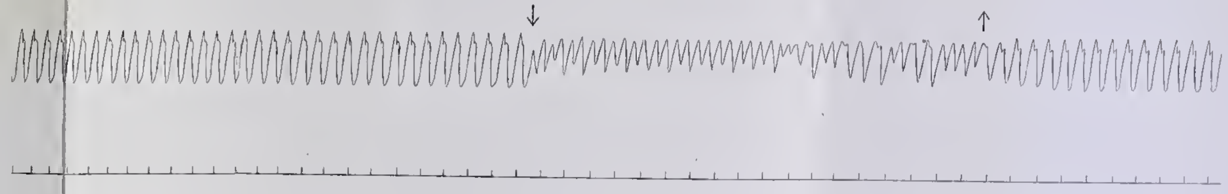

Fig. 5.

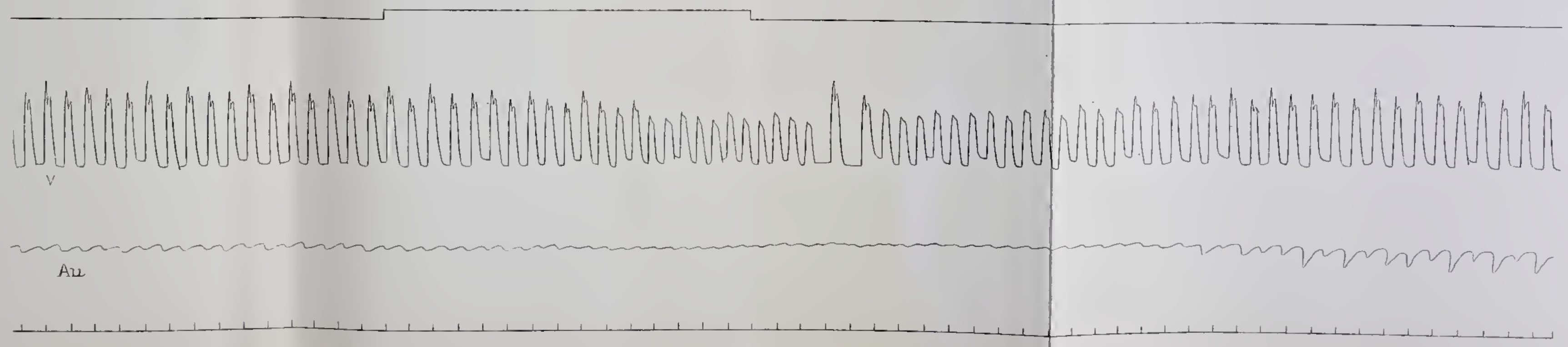

Fig. 6.

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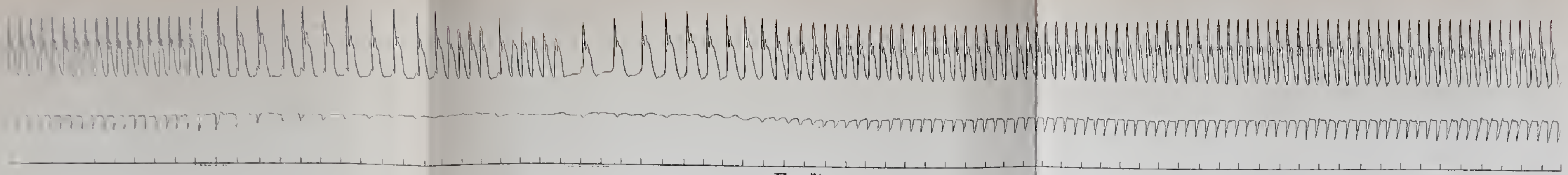

Fig. 7.

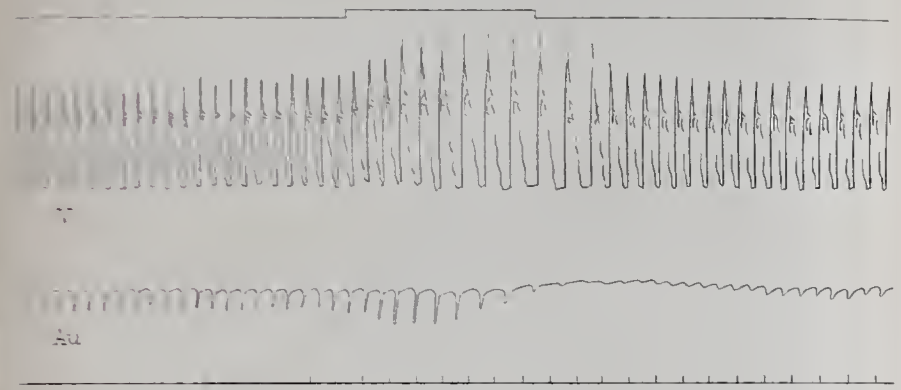

Fig. 8.

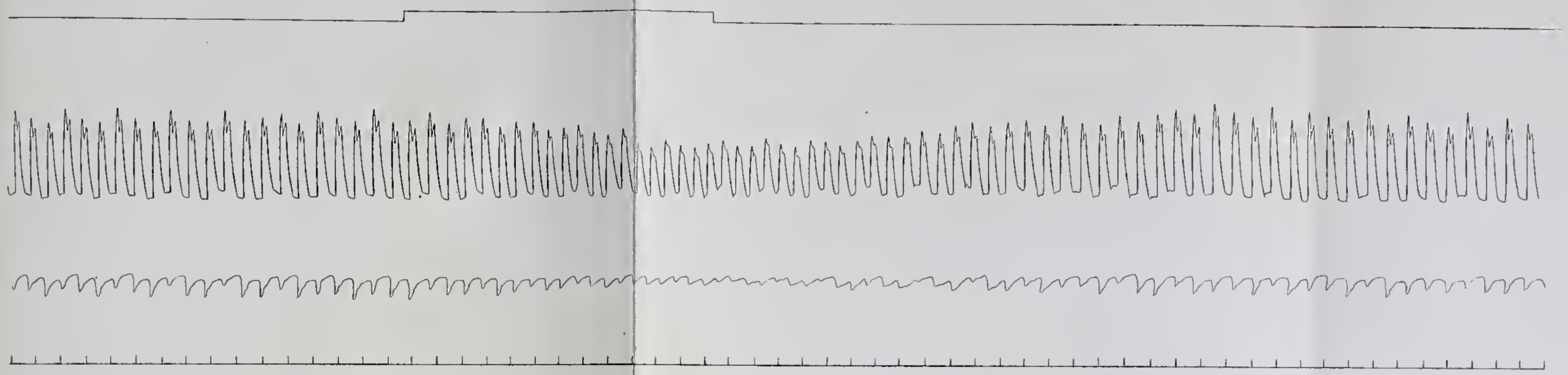

Fig. 9.

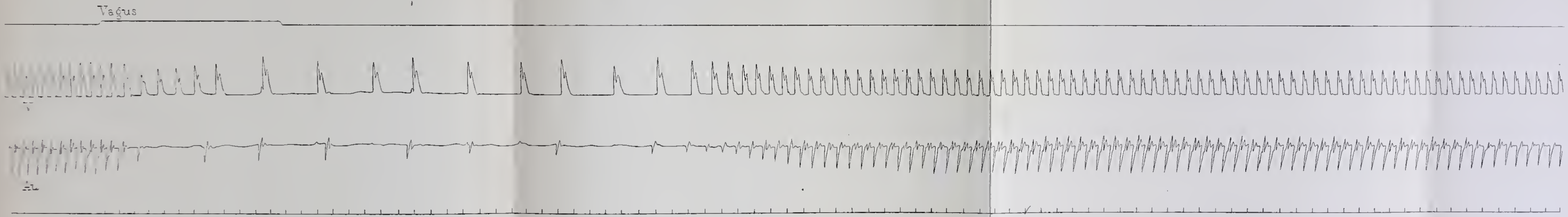

Fig. 10.

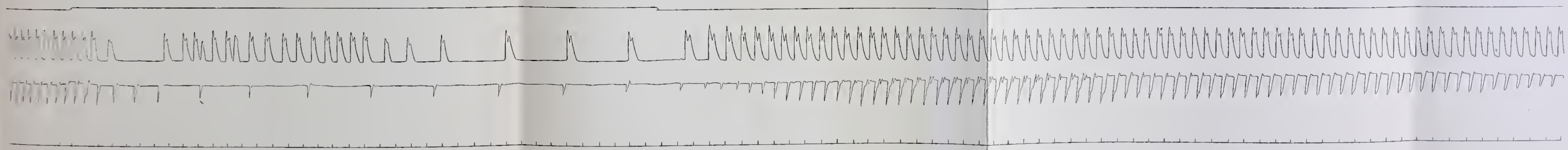

Fig. 11.

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